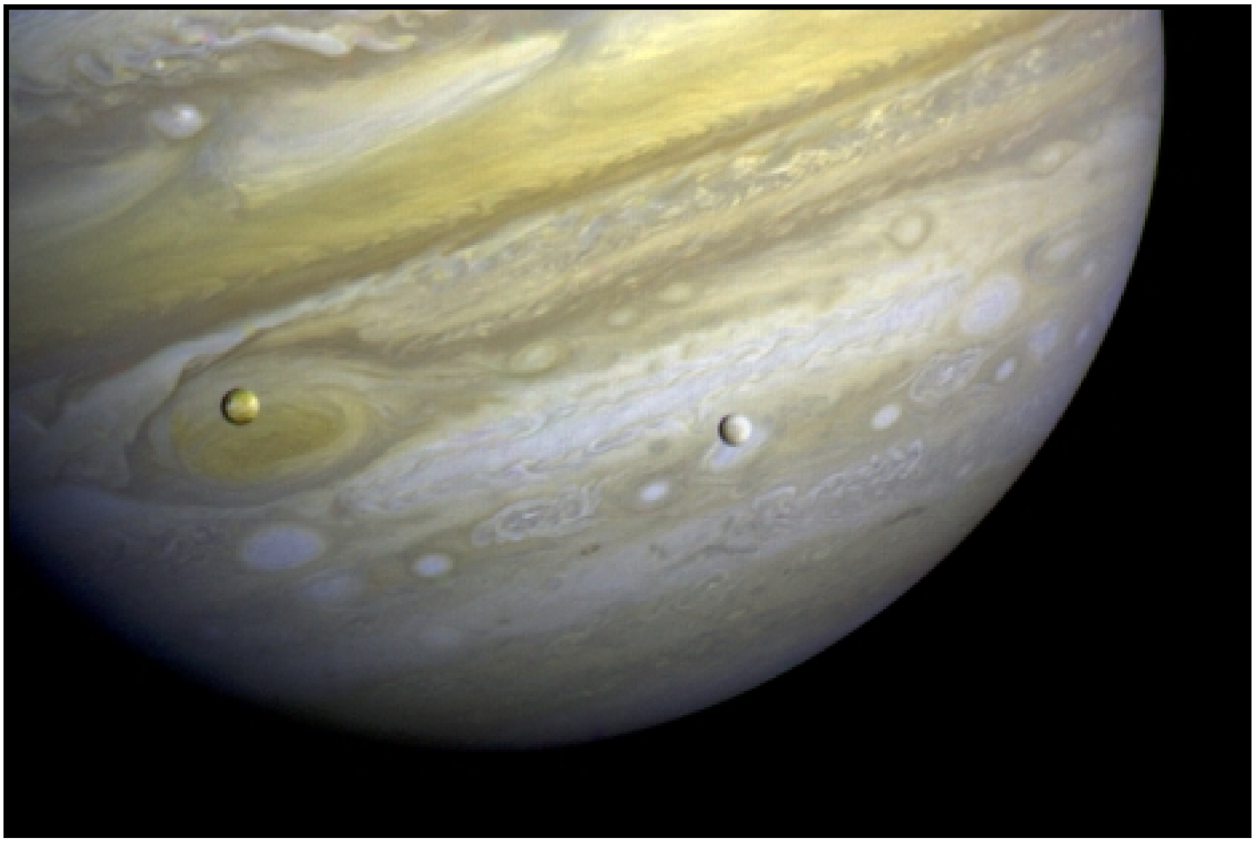

Planetary Systems Branch (SST) Overview

Principal research programs in the Planetary Systems Branch include studies of the formation of stars and planets and the early history of the solar system, studies of planetary atmospheres and climate, investigation of the dynamics of planetary rings and magnetospheres, work on problems associated with the Martian surface including resource utilization and environments for the origin of life, and other programs (chiefly theoretical) involving galaxy dynamics, radiative processes in stars and the interstellar medium, and investigation of the physical and chemical conditions in molecular clouds and star formation regions. Scientists in the branch also support NASA flight missions through participation on various mission science teams. The primary product of the Branch is new knowledge about the nature of the universe, presented and published in the open literature.

Richard E. Young
Chief, Planetary Systems Branch (SST)

ILLUMINATION OF YOUNG STELLAR DISKS

K.R. Bell

The planets in our solar system formed from a gaseous disk known as the solar nebula. Disk-shaped nebulae thought to be analogous to the solar nebula are now commonly observed around solar mass stars younger than a few million years in nearby regions such as the Taurus-Auriga molecular cloud and the Orion Nebula. Images of these disks are obtained with facilities such as the Hubble Space Telescope; spectra are obtained with the Infrared Astronomical Observatory and various ground-based observatories such as the Keck Telescope on Mauna Kea. Studying these systems provides insight into the development of our own planetary system as well as clues about the likelihood of the evolution of similar life-bearing systems around other stars.

The collapse of a molecular cloud core leads the to formation of a protostellar system composed of a star and circumstellar disk. Probably ten to fifty percent of the final mass of the star is accreted in the initial collapse, which occurs on a time-scale of several tens of thousands of years. Gravitationally induced spiral arms rapidly transport much of the remaining nebular mass inward to the central protostellar core. After perhaps a hundred thousand years, the system will consist of a central protostar, which is slowly contracting and radiating its excess gravitational energy. It will be surrounded by a disk of remnant material with a mass no greater than one quarter of the mass of the central star. This gaseous disk persists for several million years during which it is slowly depleted by accretion onto the central object, dispersal by stellar wind and radiation, and the formation of planets.

Infrared radiation from these systems can be analyzed to determine the temperature profile of the disk's surface. There are three major heat sources in these disks: heating due to the local release of gravitational energy by material slowly spiraling inward toward the central star, heating due to the capture and re-emission of stellar radiation, and heating due to the capture and re-emission of radiation from facing disk surfaces. The latter two components depend sensitively on the shape of the disk. Models which treat each disk annulus as a plane-parallel atmosphere suggest that the distance between midplane and photosphere of the disk at any given radius is largely determined by the opacity of material at the high density midplane. A schematic profile of a low-mass flux disk is shown in Figure 14. The reprocessing of radiation within the system is indicated by arrows.

In the inner regions, the disk is hot enough for dust to be destroyed at the midplane, and the disk thickness increases strongly with radius. In this region, the disk's surface is strongly heated by radiation both from the luminous protostar and from facing disk surfaces. At larger radii, where the disk is cooler, dust, which provides an additional source of opacity, is condensed throughout the disk's atmosphere. In this region, the disk's thickness increases more slowly, and stellar radiation cannot illuminate the surface. The transition between the two regimes occurs at roughly the present day orbit of the Earth and suggests that the outer planets formed under cooler conditions than would be expected if the disk were assumed to flare uniformly with radius. ❏

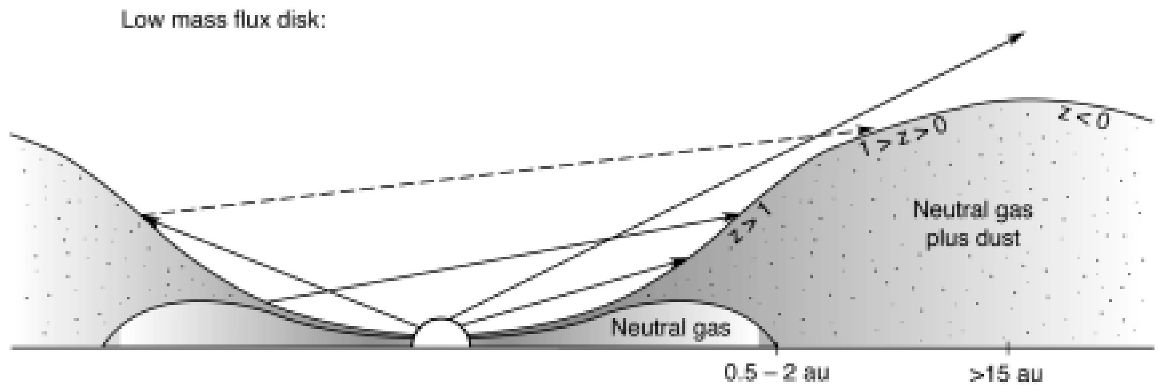

Figure 14: A schematic profile of a low mass flux disk around a solar mass star. The trend of the disk's thickness with radius, H(r), is controlled by the local opacity. Note that H(r) is proportional to r^z. In the inner regions, the star illuminates the disk's surface; at larger radii, the disk is in shadow.

DETECTION OF AN EXTRASOLAR PLANET

W.J. Borucki, D. Caldwell, D.G. Koch, L.D. Webster, J.M. Jenkins, Z. Ninkov, and R. Showen

The objective of this research is to determine the occurrence frequency and the properties of extrasolar planets.

Information on the number, size, mass, spacing, and composition of the planets in other planetary systems is needed to refine our models of planetary system formation and the processes that gave rise to their present configurations. The recent discoveries provide tantalizing glimpses of the large variety of planetary systems that exist and make it possible to begin an investigation of the role of the giant planets. To obtain information on the statistical properties of the giant inner planets, and to develop the statistical inter-dependencies of these properties, it is necessary to observe a variety of stellar spectral types and stellar compositions over a range of semi-major axes.

A small CCD photometer dedicated to the detection of extrasolar planets has been developed at Ames and put into operation at Mt. Hamilton, California. It simultaneously monitors 6000 stars brighter than 13th magnitude in its 49 square-degree field of view. Observations are conducted all night every clear night of the year. A single field is monitored at a cadence of eight images per hour, for a period of about three months. When the data are folded, in order to discover low-amplitude transits, transit amplitudes of 1% are readily detected. This precision is sufficient to find jovian-size planets orbiting solar-like stars, which have signal amplitudes from 1% to 2%, depending on the inflation of the planet's atmosphere and the size of the star.

Recent observations made with the Vulcan photometer produced over one hundred variable stars, many not previously known. About fifty of these stars are eclipsing binary stars, several with transit amplitudes of only a few percent. Three stars that showed only primary transits were examined with high-precision spectroscopy. Two were found to be nearly identical stars in binary pairs orbiting at double the photometric period and the third was found to be a high mass-ratio single-lined binary star.

The November 22, 1999 transit of a planet orbiting HD209458 was observed and the predicted amplitude and immersion times were confirmed. These observations show that the photometer and the data reduction and analysis algorithms now have the necessary precision to find companions with the expected area ratio for jovian-size planets orbiting solar-like stars.

In early November of 1999, two groups announced the discovery of a planet orbiting HD209458 in the Pegasus constellation. The symbols shown in Figure 15 shows the extinction-corrected, normalized light curve we obtained for HD209458 on November 22, 1999. Because this event was the last opportunity to observe the transit, observations were made, even though the star was setting during the transit. Consequently, only the first portion of the transit is seen. The solid line represents the predictions based on the work of Charbonneau et al. and Castellano et al. 1999. Both the limb-crossing time (25 minutes) and the measured amplitude of the transit (1.6%) are in excellent agreement.

Ordinarily, photometry is done as close to the meridian as possible to mitigate the error introduced by scintillation and rapid extinction variations that are associated with high air mass. For this reason, measurements are usually made at air-mass less than 1.5 and seldomly made at an air mass as large as 2.0. However to obtain the data on November 22nd, the measurements were made as the air mass ranged from 1.5 to 4. Figure 16 shows the measured rapid increase in standard deviation (SD) of the fluxes of the seven comparison stars at the time of the measurements. The solid curve shows the expected level of scintillation noise. The agreement between these measurements and the predictions of the scintillation noise demonstrates that the system was operating at a precision limited only by properties of the atmosphere. The observations were terminated at an air mass of four because the signal to noise ratio had dropped below 2.5 at that point. ❑

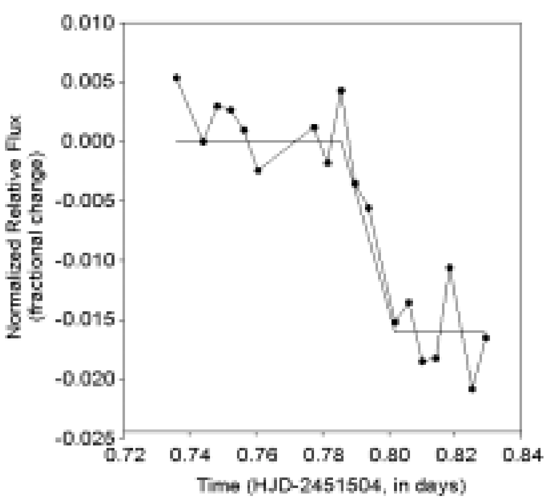

Figure 15: Comparison of the Measured and Predicted Flux for the November 22, 1999 Transit of a Planet Orbiting HD209458.

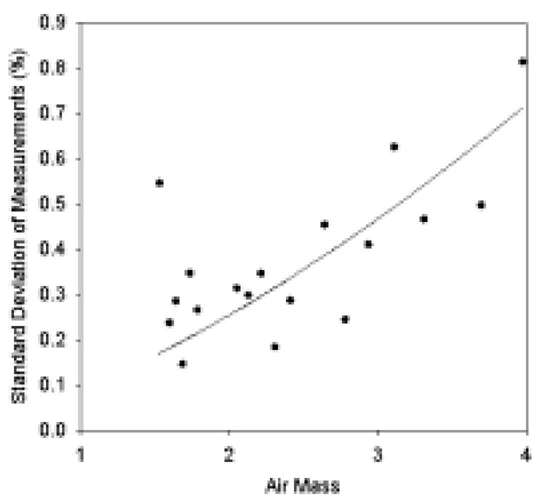

Figure 16: Comparison of the standard deviation of the fluxes of the comparison stars with the prediction of scintillation noise by Young (1974).

COMPOSITION OF DUST ALONG THE LINE OF SIGHT TOWARD THE GALACTIC CENTER

J. Chiar, A. Tielens, and D. Whittet

The composition of dust and ice along the line of sight to the Galactic Center (GC) has been investigated through analysis of mid-infrared spectra (2-13 micron) from the Short Wavelength Spectrometer on the Infrared Space Observatory (ISO). The path to the Galactic Center samples both diffuse interstellar matter and dense molecular cloud environments, by performing a phenomenological comparison with well-studied sightlines known the sample these distinct environments. We have been able to separate spectral absorption features arising in these components towards the Galactic Center. Dust absorption features along the lines of sight toward Sagittarius A* (Sgr A*) and the Quintuplet sources (GCS3 and GCS4) are the primary targets in this endeavor. Molecular cloud material is unevenly distributed across the Galactic Center. Measurements of absorption features due to abundant solid state species, such as water-ice and carbon dioxide, reveal that there is more molecular cloud material along the line of sight toward Sgr A* than the Quintuplet sources. The Sgr A* sight-line has a rich solid state infrared spectrum which also reveals strong evidence for the presence of solid methane, ammonia and formic acid in the molecular cloud ices.

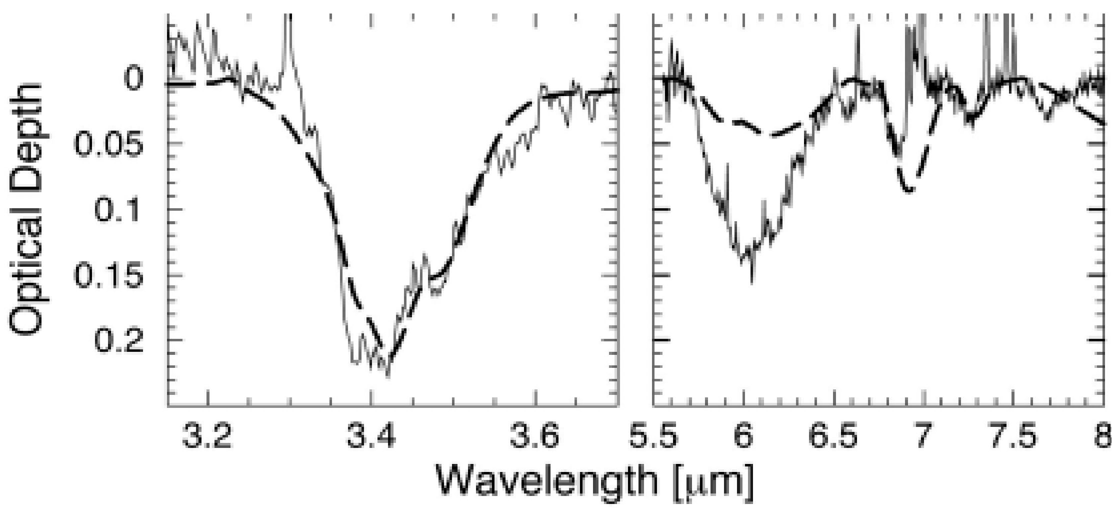

Figure 17: Mid-infrared spectrum of Sagittarius A* (solid line) compared with a laboratory HAC analog from Furton (Rhode Island College) (dashed line). The HAC spectrum is well representative of the interstellar absorption features at 3.4, 6.8 and 7.3 microns.

Hydrocarbon dust in the diffuse interstellar medium along the line of sight to the GC is characterized by absorption features centered at 3.4, 6.8, and 7.3 micron. Ground-based studies have identified the 3.4-micron feature with the C-H stretch vibration mode of aliphatic (chain-like) hydrocarbons. Prevailing theories regarding the production of this robust organic interstellar grain component assume energetic processing of simple interstellar ices (water, carbon monoxide, methane, and ammonia) present in dense molecular clouds. ISO observations have provided the first meaningful observations of the corresponding modes of these hydrocarbons at longer wavelengths, enabling us to rule out some laboratory analogs and therefore the production routes of these organics. The integrated strengths of the three observed absorption features suggest that some form of hydrogenated amorphous carbon (HAC), rather than processed ices, may be their carrier. Figure 17 shows an impressive match to the observed absorption features with a HAC produced in the laboratory by Douglas Furton (Rhode Island College). We have attributed an absorption feature that is centered at 3.28-microns in the GCS3 spectrum to the C-H stretch of aromatic (ring-like) hydrocarbons. Since this was the only feature detected, and the C-C stretch counterpart (at 6.2 micron), toward the Quintuplet region, but not toward Sgr A*, one of the key questions which now arises is whether aromatic hydrocarbons are a widespread component of the general diffuse interstellar medium, analogous to aliphatic hydrocarbons. ❑

PLANETARY RINGS

J.N. Cuzzi, J. Lissauer, I. Mosqueira, M. Showalter

In addition to the natural curiosity inspired by their unusual appearances, planetary rings present a unique dynamical laboratory for understanding the properties of collisional particle disks which might help us understand the accretion of the planets. Ames maintains the Planetary Data System's Rings Node (http://ringmaster.arc.nasa.gov/), which archives and distributes ring data from NASA's spacecraft missions and from Earth-based observatories. We now have on line the entire archive of images from the Voyager missions to the giant planets, with catalogs to help users find the images they need. We have available all the images of Saturn obtained by the Hubble Space Telescope during 1995, when the rings were seen edge-on to the Earth.

An important theoretical advance occurred in the development of a new theory for how narrow, elliptical rings, with nested elliptical orbits, preserve their shape over long periods of time in the face of the tendency of their inner orbits to precess more rapidly than their outer orbits, causing misalignment and collisional disruption. The major previous theory relied exclusively on ring self-gravity to provide the slight counteracting force needed to prevent this, but the mass implied was much smaller than that believed to lie in these rings based on other observations. This year, new physics was added to the equations of motion in the form of pressure tensors in dense particle layers that behave like traffic jams. The new physics turns out to make it more difficult for self-gravity to maintain the alignment of the nested orbits, and boosts the needed mass density into much better agreement with observations.

New observational results were also obtained from analysis of extensive Hubble Space Telescope (HST) observations of Saturn's rings, taken over the last three years as the ring opening angle increased as seen from Earth and Sun (Figure 18). These new observations, taken in eight different colors (several not observable from the Earth) show for the first time that the ring brightness varies with phase angle but not with ring opening angle. This makes it clear that the reflectivity is caused by multiple scattering within a granular regolith on large ring particles, but not between ring particles. This led to the realization that the ring particles are less red than previously determined from Voyager observations at a higher phase angle. Furthermore, the HST data provide evidence for increased absorption by water ice in certain parts of the rings relative to others, indicating differences in either the surface coverage of surface grain size on the particles. Also, the optically thinner parts of the rings, where the particles have been known to be darker (its inner or C ring, and the Cassini division lying between the main A and B rings), reveal an unassigned absorption feature in the 850-nanometer spectral range. Tentative evidence for such absorption had been hinted at in earlier observations, but the new observations not only verify its existence, but clearly show that the absorber is localized to the C ring and the Cassini Division. We obtained a high-resolution HST image of Saturn's faint G ring that shows that the radial distribution of large particles is similar to that of tiny dust grains observed by Voyager and Galileo. The HST data are being used now in planning Cassini observations of Saturn that will begin in 2004.

Finally, new analyses of Voyager data show that the bright knots and clumps in the curious F ring of Saturn are transient. A few are seen to appear and then dissipate in a matter of days; these are probably caused by puffs of debris from impacts of meteoroids into the larger ring bodies. However, most clumps persist for a matter of months and are probably caused by the more gentle collisions among the bodies themselves. In addition, smaller ring clumps are periodic and show the characteristic spacing one would expect from gravitational interactions with the nearby 'shepherding' moon, Prometheus. Our dynamical models suggest that this periodic tug between the ring and moons may also give rise to a random component in Prometheus' orbit, as has been observed in recent HST images. ❑

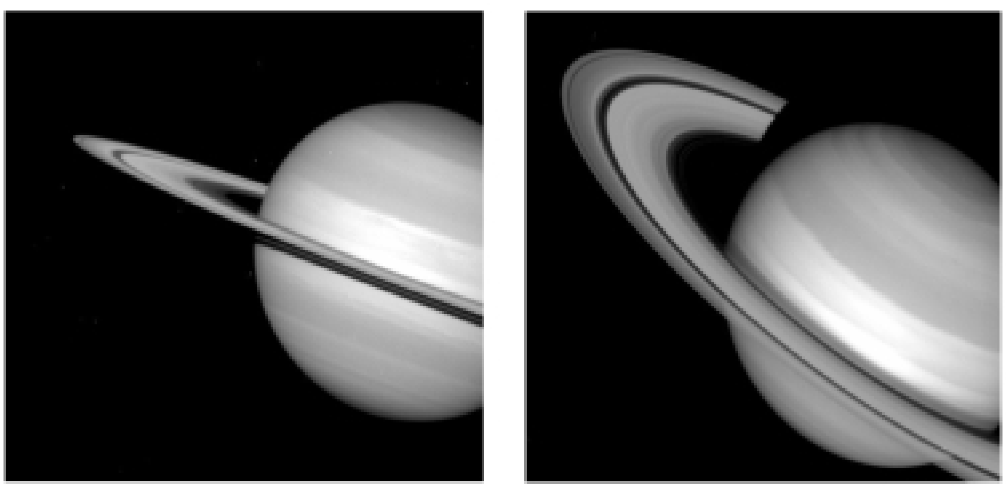

Figure 18: Typical HST images of Saturn's rings at two different opening angles. The spatial resolution is adequate to easily resolve color and compositional differences between many different regions of the rings.

PRIMARY ACCRETION IN THE PROTOPLANETARY NEBULA

J.N. Cuzzi, R.C. Hogan, S. J. Desch, J.M. Paque, and A.R. Dobrovolskis

‘Primitive’ objects in the meteorite record represent the first large bodies to accumulate in the protoplanetary nebula – a vast data set that has had little context for interpretation. The accretion of primitive bodies almost certainly occurred in the presence of gas. Ames’ efforts focus on numerical modeling of particle-gas interactions in turbulent flows, and understanding meteorite properties in the light of theoretical models.

A dense layer of particles orbiting in the midplane of a protoplanetary nebula at close to the unperturbed (or Keplerian) orbital rate, generates a vertical velocity shear and associated turbulence, which prevents the particles from settling completely to the midplane and becoming gravitationally unstable (i.e. from collapsing into planetesimals). However, it was thought possible that damping of the turbulence by the particles themselves might allow the particles to settle into an unstable layer. This year, a study was completed which modeled the evolution of such a layer that incorporated a new model for the damping effects of the particles on their self-generated turbulence. While turbulence damping does flatten the layer, previously neglected terms were uncovered during the study that disperse the layer even more effectively, with the end result that the layer is even less flattened (more stable) than previously believed.

In prior years, Ames developed a hypothesis to explain the prevalence of millimeter-sized ‘chondrules’ in chondritic meteorites by the mechanism of preferential concentration of aerodynamically selected particles in three-dimensional turbulence. The theory makes specific predictions as to the relative abundance distribution of the concentrated particles. To test the theory, we disaggregated four primitive chondritic meteorites and measured the relative distribution of particles as a function of the product of their radius and density (the important determinants of the particle’s aerodynamic stopping time). Comparisons of the theoretical predictions (open symbols) and meteorite data (filled symbols) are shown in Figure 19 for these four meteorites. Relative abundances are plotted as functions of the Stokes number (St), or ratio of particle stopping time to Kolmogorov eddy time. It has been realized for several years that the concentration is maximized for particles with St =1, but not that the distribution function was so narrow. We also completed a multi-fractal theory to predict the magnitude of turbulent concentration at much higher Reynolds numbers than achievable numerically. The concentration is so large that mass loading (the feedback effect of the particle phase on the gas turbulence itself) must be considered before further modeling efforts can proceed. This theory might be of interest to terrestrial cloud modelers as well.

The prevalence of chondrules in meteorites (up to 80% in some classes), implies that they were pervasive in the nebula. Mineralogical studies imply that the favored melting process occurred on short time-scales, over limited spatial scales, and in a relatively cool environment. Lightning, often observed in dry turbulent environments on the Earth, has been studied before and rejected by others. We combined two new insights: the ability of ‘triboelectric charging’ due to collisions between chemically dissimilar grains (large silicate chondrules and fine metal grains) to produce large positive charges on the silicate chondrules, and the ability of turbulent concentration to concentrate the charged chondrules and build up sufficient voltage to initiate large lightning strokes. Nebula lightning might also have implications for protoplanetary nebula chemistry. ❑

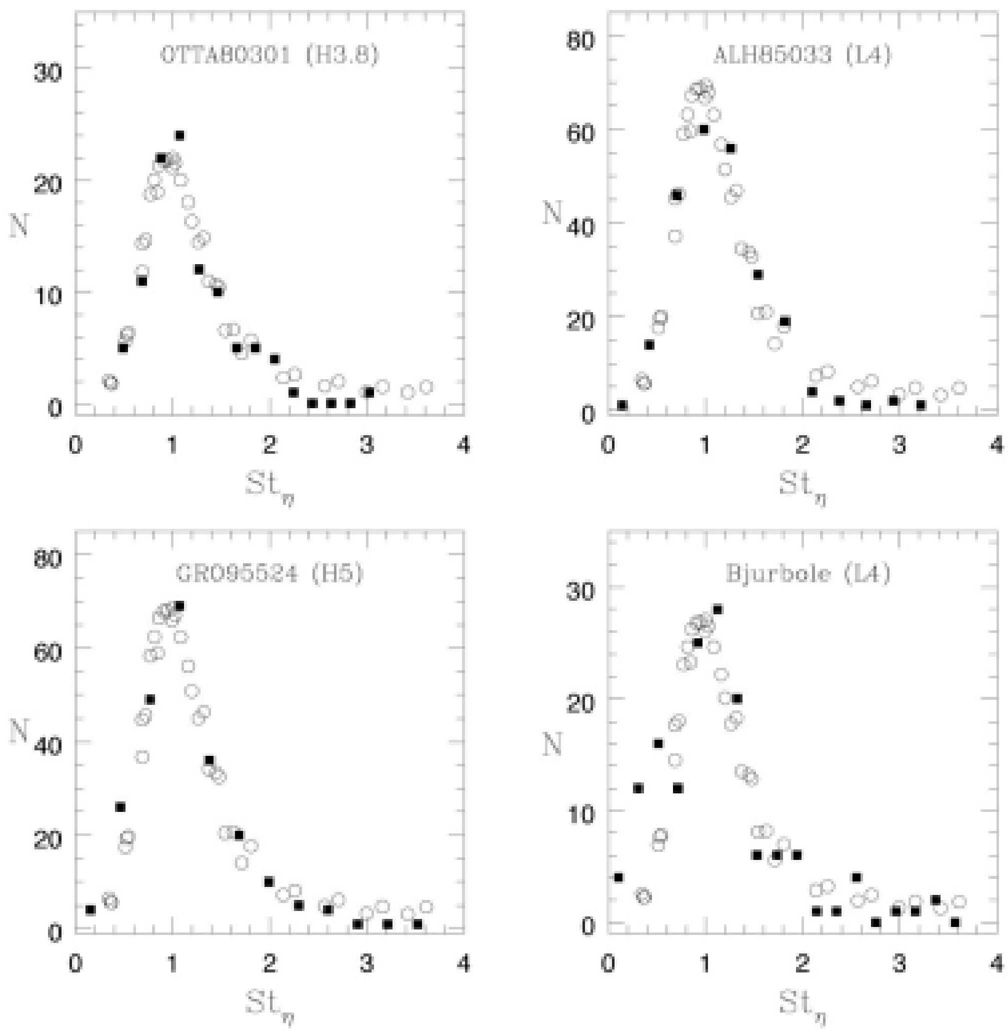

Figure 19: Predicted (open symbols) and observed (filled symbols) distributions of particle size-density product as functions of their aerodynamic stopping time, as normalized to the Stokes number St (subscripted here by the Kolmogorov scale) by dividing by the Kolmogorov eddy turnover time. The observed data are from four different primitive meteorite samples. The agreement is quite good. We also found (not shown here) that using the actual density of each object rather than the average density of all objects noticeably improves the fit, as expected if aerodynamic sorting had operated to determine the chondrule size distribution.

THE CALCULATION OF MOLECULAR OPACITIES

R. Freedman

The theoretical modeling of the properties and emergent spectra of extra solar giant planets and brown dwarfs requires an accurate and detailed knowledge of the sources of molecular opacity in these objects. In the past few years, many new extra solar planets and brown dwarfs have been discovered using new observational techniques and better, and larger telescopes. To better understand the physical properties of these new objects and to relate their properties to the properties of other solar systems, astronomers have been using computer-generated models to reproduce their observed properties. This allows a direct comparison between theory and observations and helps to constrain physical properties such as mass, radius and chemical composition. These objects span the range between the gas giants of our own solar system (Jupiter), and objects almost large enough to burn hydrogen in their interior and thus become stars (brown dwarfs). An accurate theoretical model requires a thorough knowledge of the molecular opacities of a large number of different species, since the temperature in the atmospheres of these objects spans a range from 100 degrees Kelvin up to several thousand. Because of the wide range of physical conditions encountered, modelers need molecular opacities up to a range of temperatures that go far beyond the normal range of molecular data from laboratory studies. The purpose of this research is to extend the range of available molecular opacities up to the higher temperatures needed by the modelers.

This has been accomplished by using a combination of theoretical techniques combined with available observational data to predict lines of various molecules such as CH_4, VO, and CrH. As an example of what has been accomplished, consider the cases of CH_4, H_2O, and TiO: (methane, water, and titanium oxide). The list of spectral lines was extended for all these species to include lines that will become important at higher temperatures, even though these lines are practically unobservable at room temperatures. Water and methane, in particular, are very important sources of opacity in these objects and the inclusion of adequate opacity is very important in a proper evaluation of their spectra and in constructing physically realistic models. In doing this work, the researcher made use of the work of other Ames researchers especially the work of Dr. David Schwenke of the Computational Chemistry Branch. Comparison with observations shows that more work remains to be done to provide opacities that are physically realistic at the highest temperatures. This is especially true for methane and less so for water. Even so, the latest models for objects such as the brown dwarf Gl229B (Gliese 229B) show good agreement with the best available observations. ❏

THE CENTER FOR STAR FORMATION STUDIES

D. Hollenbach, K.R. Bell, P. Cassen, and G. Laughlin

The Center for Star Formation Studies is a consortium of scientists from the Space Science Division at Ames and the Astronomy Departments of the University of California at Berkeley and Santa Cruz. This consortium, under the directorship of D. Hollenbach, conducts a coordinated program of theoretical research on star and planet formation and supports postdoctoral fellows, senior visitors, and students.

Consortium members meet regularly at Ames to exchange ideas and present informal seminars on current research. Each Summer, a week-long workshop on selected aspects of star and planet formation is convened.

In July 1999 the Ames members of the Center together with members of the Stratospheric Observatory for Infrared Astronomy (SOFIA) team held an international workshop entitled “SOFIA and Star Formation.” The week-long workshop, held on the University of California at Santa Cruz campus, had approximately 175 attendees. Ames scientists E. Erickson and D. Hollenbach were invited to speak and an afternoon discussion on “Key Star Formation Projects for SOFIA” led by L. Caroff (Ames). One purpose of this workshop was to bring theoretical and observational astronomers together with the instrumentalists working on SOFIA instruments in order to stimulate new ideas for SOFIA observational projects related to star formation.

One focus of the 1999 Ames portion of the research work of the Center, involved the effect of ultraviolet radiation from young massive stars on the star-forming clouds of gas and dust that typically surround them or lie close to them. These clouds, called “Giant Molecular Clouds” or GMCs, typically contain 100,000 solar masses of gas and dust and are the dominant sites of star formation in galaxies. The GMCs consist primarily of cold molecular hydrogen gas found in a very ‘clumpy’ structure bound together by gravity. Thousands of stars are formed in each cloud before it is dispersed in roughly ten million years by the ultraviolet radiation from the most massive stars formed in the GMC. The ultraviolet radiation photoevaporates the clumps in a GMC, destroys the molecules, and heats the gas until the thermal pressure creates a catastrophic expansion of the GMC. These processes disperse the cloud and terminate the star formation process, thereby helping to explain why GMCs do not convert higher fractions of their mass into stars before evaporating into the diffuse interstellar medium. The heating of the gas leads to the emission of characteristic infrared spectra that can be analyzed to determine the physical and dynamical properties of the evolving clouds.

Another focus of the Ames portion of the Center research in 1999 involved the formation and propagation of spiral density waves in the orbiting disks of gas and dust that circle a newly formed star and which ultimately form planets. These spiral density waves affect the evolution of the density and angular momentum in these disks, and therefore the planet-forming characteristics of the disks. Through a combination of analytic analysis and numerical simulations, it was shown that two competing hypotheses explaining the cause of spiral structure in self-gravitating disks, had an underlying unity. This provided a much better understanding of how mass and angular momentum are transported through protostellar disks. This work could also be generalized to the self-gravitating disks, which characterize galaxies, and thereby cleared up a long-standing debate in the galactic structure community.

The theoretical models of the Center have been used to interpret observational data from NASA facilities such as the Infrared Telescope Facility (IRTF), the Infrared Astronomical Observatory (IRAS), the Hubble Space Telescope (HST), and the Infrared Space Observatory (ISO, a European space telescope with NASA collaboration), as well as from numerous ground-based radio and optical telescopes. In addition, they have been used to determine requirements on future missions such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the proposed Space Infrared Telescope Facility (SIRTF). ❑

MARS ATMOSPHERE AND CLIMATE

J.L. Hollingsworth, R.M. Haberle, and J. Schaeffer

Furthering our understanding of the global atmospheric circulation on Mars is the focus of this research at NASA Ames. As in Earth's atmosphere, Mars' atmospheric circulation exhibits variability over a vast range of spatial and temporal scales. Some of these processes are driven by similar physical processes (e.g., Hadley circulation cells; global-scale thermal tidal modes; planetary waves forced via flow over large-scale orographic complexes like Earth's Himalayan plateau; and developing, traveling and decaying extra-tropical weather cyclones associated with pole-to-equator thermal contrasts). Other sources of variability arise from distinctly martian physical mechanisms (e.g., condensation (sublimation) during the winter (summer) season of the atmosphere's primary chemical constituent (predominantly CO_2), and regional- and global-scale dust storms). Ultimately, these investigations aspire to improve our knowledge of the dynamics of the planet's present environment and past climates, and from a comparative planetology perspective, to better understand similar processes that govern the dynamics of the Earth's climate.

In this endeavor, the primary tool used is the Ames Mars General Circulation Model (MGCM). The MGCM is a time-dependent, three-dimensional, numerical model of the atmosphere's hydrodynamic state as determined by self-consistent algorithms for radiative (e.g., solar and infrared absorption, emission and scattering in the planet's tenuous and frequently dust-laden atmosphere) and near-surface processes (e.g., a boundary-layer dissipation associated with atmospheric turbulence). In parallel efforts, spacecraft data from the recent Mars Pathfinder mission and the on-going Mars Global Surveyor (MGS) mission are utilized to validate the climate-simulation results, while at the same time, both mechanistic and full-up MGCM simulations can offer a global context for the remotely sensed data.

Investigation of the middle and high latitude meteorological environment using a very high-resolution version of the MGCM has recently been conducted. This research is motivated by Hubble Space Telescope (HST) observations of 'comma'-shaped cloud formations and large-scale dust activity in the polar region during early northern spring and summer, and, by MGS Mars Orbiter Camera (MOC) imaging of condensate cloud structures in the polar environment during this season. Modeling at high spatial resolution is necessary in order to illuminate processes important to local and regional dust activity, as well as condensate cloud formation, structure, and evolution within the edge of Mars' seasonal polar caps. It has been found that near-surface and upper-level fronts (i.e., narrow zones with enhanced mass density, momentum and thermal contrasts within individual extra-tropical cyclones) can form in Mars' intense high-latitude baroclinic zone, and the associated frontal circulations are sufficient to raise dust in high latitudes.

Shown in Figure 20 in a spherical projection view, are examples of these results for simulations that include recent MGS Mars Orbiter Laser Altimeter (MOLA) topography in the climate model. Solid contours correspond to potential temperature and arrows correspond to the instantaneous horizontal wind. Near the prime meridian (i.e., the center longitude of each panel), a clear rarefaction, stretching, and deformation of the temperature field can be seen. This rarefaction is caused by intense local circulations associated with traveling weather systems in middle latitudes (i.e., transient baroclinic eddies). These systems are Mars analogs of traveling high- and low-pressure systems which occur in the Earth’s extra-tropics associated with instability of the tropospheric jet stream. Note the profound sharpness of the frontal systems as well as their vast north-south (i.e., meridional) scale. The weather fronts appear to be favorably triggered near the high-relief regions of the Western hemisphere and subsequently intensify rapidly in the low-relief areas to the east. Based on low horizontal resolution modeling of Mars’ transient baroclinic waves, the latter geographic region corresponds to a preferred region for cyclone development (i.e., a ‘storm zone’).

Both the data analysis and modeling efforts can significantly enhance the assessment of Mars’ present climate, and thereby will provide a more comprehensive climate database for future missions scheduled during the Mars Surveyor program. ❑

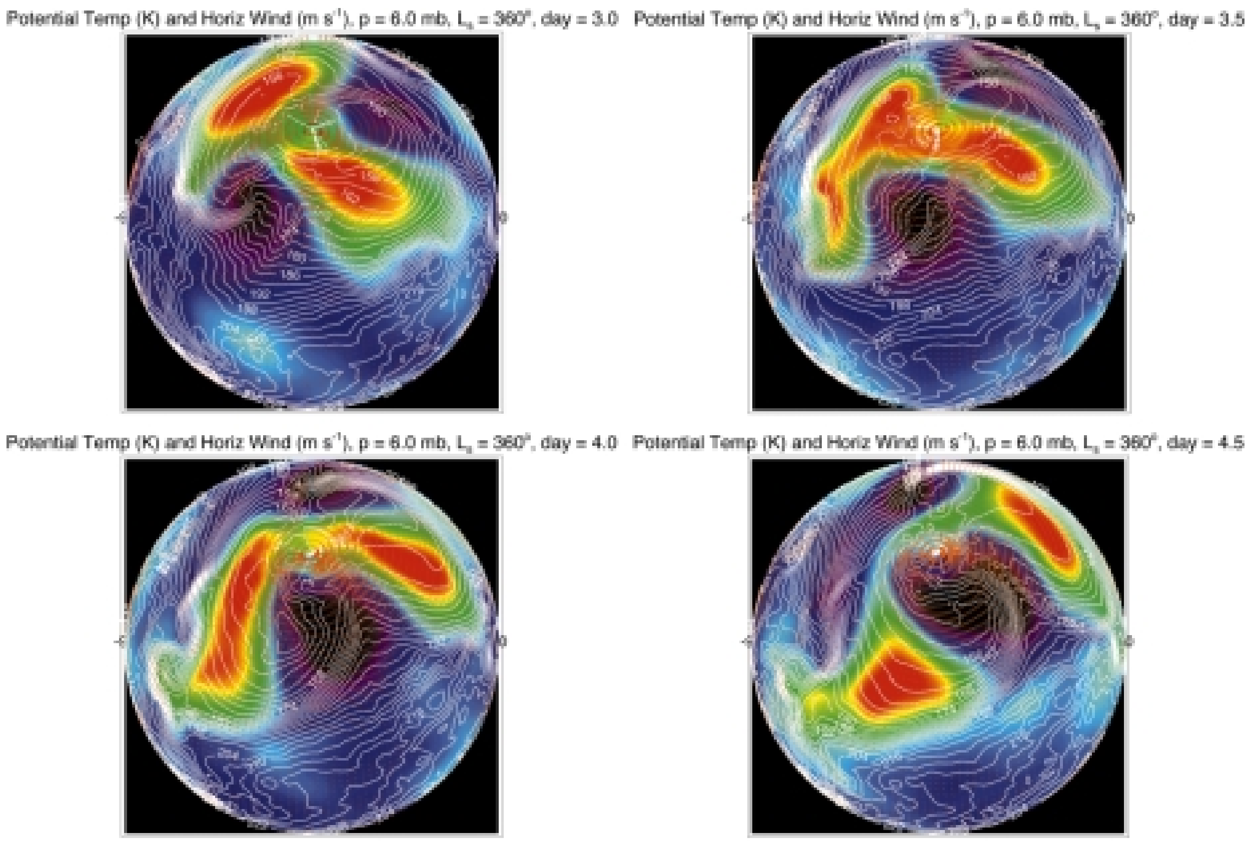

Figure 20: Potential temperature (degrees Kelvin) and horizontal wind (m/s) at the 6 mbar surface, and instantaneous surface pressure anomaly (color) on (a) day 3.0, (b) day 3.5, (c) day 4.0, and (d) day 4.5, in a MGCM numerical experiment using MGS/MOLA topography. High (anti-cyclonic) pressure anomaly is red and low (cyclonic) pressure anomaly is black/purple. The temperature contour interval is 3 degrees Kelvin.

STABILITY AND CHAOS IN PLANETARY SYSTEMS

G. Laughlin

One of the major news stories of the year was the detection of multiple planets around a Sun-like star (Upsilon Andromedae). Aside from being a 'first' detection, this discovery was very interesting because the arrangement of the three planets in the Upsilon Andromedae system is drastically different from the arrangement of our own system. The two outer Upsilon Andromedae planets are considerably more massive than Jupiter, and they have orbits which are much more eccentric than those of the major planets in our system. However, the radial velocity observations used to make the discovery can only determine a lower limit for the planetary masses. Furthermore, there were several different data sets compiled by competing teams of observers. Important questions thus remained, both of which were addressed by Ames-based theoretical research: a) what is the true mass of the planets, and b) which set of published orbital parameters best represents the true configuration of the system?

Work in fiscal year 1999 focused extensively on these questions, and examined other aspects of the general problem of planetary orbital stability. By performing over ten billion years worth of numerical integrations covering many different configurations that are compatible with the observed data from the Upsilon Andromedae system, the Ames research effort significantly narrowed the possible orbital parameters of the system. It was proved that in order for the system to survive over the 2-3 billion-year age of the parent star, the orbital planes of the planets are being viewed close to edge-on. This indicates that the companion masses are close to their minimal, nominal values, and are hence true planets. It was also shown that the observations of the UC Berkeley team were likely to be the most accurate. The Ames effort has now been confirmed by several other teams of researchers.

In a related line of research, large-scale numerical experiments have shown how the effects of the close passage of a binary pair of stars can disrupt an otherwise orderly system of planets (see Figure 21). This effect is now understood to be important in the dense open clusters that are the birthplace of many stars. In the fiscal year 1999 research, the simulations were extended to study the ramifications of this process for the history and future of our own Solar System. The research showed that the Solar System has existed more or less in isolation since its birth. The nearly perfectly circular orbit of Neptune indicates that the Sun has never suffered a significant encounter with another star, suggesting that low-density regions of star formation such as the Taurus Molecular Cloud are the most promising nurseries for planets that eventually develop Earth-like environments. One interesting auxiliary result was the calculation of the odds of Earth being ejected or captured from the Solar System by another star prior to the Sun's red giant phase: a scant one part in one hundred thousand! ❑

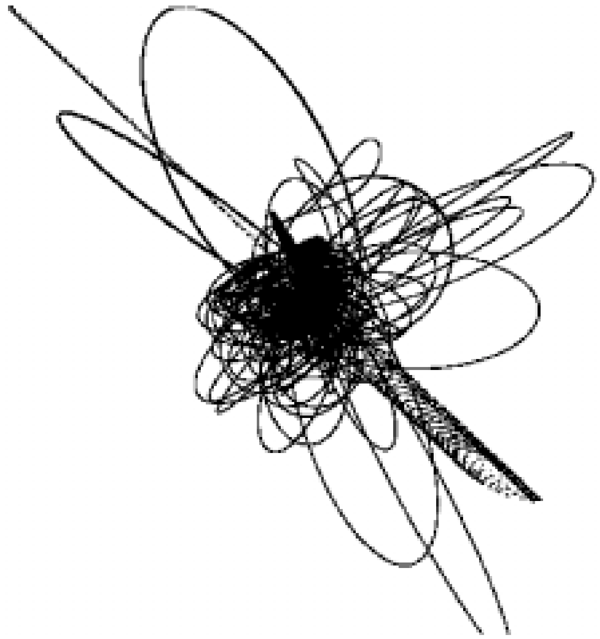

Figure 21: This computer simulation shows the outcome of a close encounter between a red dwarf binary pair and the Sun-Earth system. The red dwarf pair approaches the Sun from a direction perpendicular to the figure plane. Earth is almost immediately handed off to the smaller star and stays with that star for three long, looping excursions. After slightly more than 1000 years Earth is recaptured by the Sun, and remains in a solar orbit for the next 6500 years, as the Sun suffers many complicated close encounters with the other stars. After 7500 years, Earth is captured into orbit around the larger red dwarf star, and soon there after this star escapes with the Earth in tow. This particular simulation is one of several million performed in order to understand how planetary systems are affected by encounters with the other stars.

STABILITY OF UPSILON ANDROMEDAE'S PLANETARY SYSTEM

J.J. Lissauer and E. Rivera

The objectives of this project are to study the dynamical properties of planetary systems that are consistent with the observational data on the three-planet system orbiting the nearby main sequence star Upsilon Andromedae. We find that some configurations consistent with the data originally announced by the discovery team are stable for at least one billion years, whereas in other configurations planets can be ejected into interstellar space in less than 100,000 years. The typical path to instability involves the outer planet exciting the eccentricity of the middle planet's orbit to such high values that it ventures close to the inner planet. In some stable systems a secular resonance between the outer two planets prevents close approaches between them by aligning their longitudes of periastron (i.e., the orientations of their elliptical orbits). In relatively stable systems, test particles (which can be thought of as representing asteroids or Earth-like planets that are too small to have been detected to date), can survive for long times between the inner and middle planets, as well as exterior to the outer planet. No stable orbits between the middle and outer planets were found. ❑

IDENTIFICATION OF NITRILES IN THE INTERSTELLAR MEDIUM

Y.J. Pendleton

The interstellar 4.62-micron band (2165 wave number) may be an important contributor to the cyanide (CN) inventory of material available for incorporation into newly forming planetary systems. This band is seen in absorption along lines-of-sight which pass through icy grains in front of embedded protostars. Therefore, the identification of the interstellar band is important for two reasons: for the astrophysical understanding of organic material in the dense cloud environment, and for the potential relevance to the origin of life as extraterrestrial sources of CN groups may have been necessary if the early Earth had a non-reducing environment.

New laboratory results indicate that carbon, nitrogen, oxygen, and hydrogen are active participants in the carrier of the interstellar 4.62-micron band. Results of ion bombardment of interstellar ice analogs readily produce a band in laboratory residues that is remarkably similar in profile and peak position to that seen in the dense interstellar medium. A shift in band position resulting from deuterium substitution demonstrates that hydrogen is a component of the carrier in the laboratory-produced 4.62-micron band. This is in contrast to premature identifications of the isocyanate anion (OCN^-), recently published by other groups. Irradiation of ices through ion bombardment allows testing mixtures that include solid nitrogen, N_2, a possible source of the available nitrogen in dense cloud ices. If the atmosphere of the early Earth were not overly reducing, as some studies indicate, extraterrestrial sources of CN-bearing molecules may have been necessary for the origin of life, the *in situ* production of prebiotic molecules containing the cyanogen bond would have been difficult. Therefore, the identification of the interstellar 4.62-micron band may include the identification of an extraterrestrial source of CN. ❑

IDENTIFICATION OF HYDROCARBONS IN THE DIFFUSE INTERSTELLAR MEDIUM

Y.J. Pendleton and L.J. Allamandola

Of relevance to both astrophysics and astrobiology is the nature and evolution of organic material in the interstellar medium (ISM). This is because the ‘final’ material available for incorporation into planetary systems will determine, in part, the composition of primitive planetesimal bodies, including those capable of delivering organic material to planets within habitable zones. One interstellar feature of primary relevance, the 3.4-micron hydrocarbon absorption band, has been the focus of a recent investigation into the origin and evolution of the carbonaceous component of the diffuse interstellar medium. The remarkable similarity of the interstellar 3.4-micron band to that seen in the extract of carbonaceous meteorites has further spurred the interest in the origin the $-CH_2-$ and $-CH_3$ groups that result in the interstellar band.

Organic residues created in the laboratory, through the energetic processing of ice mixtures and through electric discharge experiments on hydrocarbon plasmas, have resulted in many claims of spectral matches to the interstellar 3.4 micron band. The laboratory work has been essential in revealing much about the nature of the carrier, and there is consensus that the interstellar band arises from saturated aliphatic hydrocarbons. However, the exact identity of the species responsible for the interstellar band has not yet been revealed. In an effort to further constrain the properties of the true carrier of the interstellar bands, the 3.4-micron laboratory band has been investigated further through the compilation of a database of hydrocarbon candidates from astrophysics laboratories around the world. The laboratory candidates have been compared in detail over the 2-9 micron range to the interstellar data from ground-based, airborne, and space observations. Many candidate materials can now be ruled out on the basis of constraints placed upon them from the interstellar data. The interstellar line of sight used in this comparison is toward a star that lies behind the primarily diffuse interstellar medium dust, therefore contributions from dense molecular cloud ices are insignificant. The Infrared Space Observatory has provided a comprehensive view of this sight line, and it reveals the absence of any strong absorption bands in 5-8 micron portion of the interstellar spectrum. The upper limit of the hydrocarbon bands in the 5-8 micron region to those detected at 3.4 microns provides useful constraints upon the laboratory residues. Most of the laboratory residues yield large absorptions in the 5-8 micron region, especially those produced through the processing of ices. The most likely candidates remaining are those produced through plasma processing of hydrocarbons. This is consistent with recent reports of the 3.4-micron hydrocarbon absorption detected in the outflow of a carbon star rich in the acetylene (C_2H_2) molecule. Observations of additional interstellar lines-of-sight through diffuse interstellar medium dust and additional laboratory experiments aimed at the questions posed in this study will be the next steps along the path towards identifying the hydrocarbons in the diffuse interstellar medium. Dust from the diffuse ISM is incorporated into dense molecular clouds, out of which the next generation of stars and planetary systems form. Identification of the diffuse ISM hydrocarbons, which appear so similar to those seen in carbonaceous meteorites, is important to pursue. ❑

HYDRODYNAMIC SIMULATIONS OF ASTEROID IMPACTS ON VENUS

K. Zahnle and D.G. Korycansky

Impact cratering is strongly affected by the presence of an atmosphere. Our solar system offers four relevant targets: Venus, Titan, Earth, and Mars. Our greatest concern is with the Earth, but Venus is the best subject to study, as its atmosphere is about 100 times thicker than the Earth’s, and the surface of Venus is randomly peppered with a thousand craters, most of which are apparently little altered since their creation. Thus Venus provides the ideal testbed for theories of atmospheric permeability to stray cosmic bodies there is both strong atmospheric interaction and enough craters to provide ground truth to calibrate our results.

In this study a number of 2D high-resolution hydrodynamical simulations of asteroids striking the atmosphere of Venus were performed. The computations used ZEUS, a grid-based Eulerian hydrocode designed to model the behavior of gases in astrophysical situations. The numerical experiments address a wide range of impact parameters (velocity, size, and incidence angle), but the focus is on 1, 2, and 3 km diameter asteroids, as these are responsible for most of the impact craters on Venus. Asteroids in this size range disintegrate, ablate, and decelerate in the atmosphere, yet retain enough impetus to make large craters when they strike the ground. Smaller impactors usually explode in the atmosphere without cratering the surface.

In the simulations, the impactor is broken up by aerodynamic forces generated by the bolides' rapid deceleration and the shearing flow that develops around it. There results a complicated and turbulent flow at high Mach number, featuring a broad range of exponentially growing unstable waves. The simulations are sensitive to small differences (both physical and computational) in the initial conditions of the computation. We find that the shape, resolution, velocity, or other details of the impact can strongly influence which wavelengths grow first, and how quickly. The evolution of each individual impact is unique, highly chaotic, and sensitively dependent on details of the initial conditions. Atmospheric permeability thus becomes somewhat probabilistic. One lumpy object might fail to reach the surface, while another object identical save for different lumps might leave a 10-kilometer crater. The impact process is chaotic at some level; we have concentrated on extracting robust and useful results from the welter of detail that emerges from the numerical hydro-code simulations. The sensitivity of the computational results to seemingly innocuous and inconsequential differences in the model appears to be a real, physically-based characteristic of the impact process, generated by the nonlinear development of the hydrodynamical instabilities. The chaotic character of the impact process adds extra scatter, as it were, to the distribution of results that would already exist due to variations in the parameters of incoming impactors, such as shape, impact velocity, etc.

That most of the larger impactors disintegrate by shedding fragments generated from hydrodynamic instabilities led us to develop a simple heuristic model of the mechanical ablation of fragments based on the growth rates of Rayleigh-Taylor instabilities. In practice, the range of model behavior can be described with one free parameter. This 'ablation' model supplements the more traditional 'pancake' model that treats the impactor as a single hydrodynamically deforming body. The two models have different and somewhat overlapping realms of validity. The key distinction between large and small impactors is that compression waves can cross the smaller impactor before the hydrodynamic instabilities mature, thus involving the whole object in the hydrodynamics. By contrast, the larger impactor can have its front face stripped off before the trailing hemisphere is noticeably distorted. For Venus the pancake model generally works better for impactors smaller than 1-2 kilometers diameter, and the ablation model generally works better for impactors larger than 2-3 kilometers. ❑